Chapter Twelve

Idea-Sustain: An Aid for Environmentally Friendly Product Lifecycle Design

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Products make substantial impact on environment. Design for Environment (DfE) is an approach to design where all the environmental impacts of a product are considered over the entire life cycle of a product. However, unlike cost and performance, use of environmental criteria and DfE is far from part of mainstream designing. From descriptive studies we found that design can substantially affect the impact created by a product. Designers in general are not considering environmental impact as a criterion, and current support is inadequate in terms of integrated, sustainable product development where design and impact estimation are seamlessly integrated.

Life Cycle Assessment (LCA) is arguably the most promising and scientifically defendable method for estimating environmental impacts of a product during its lifecycle. Like DfE guidelines, LCA tools are not well integrated with design process and tools. A new integrated platform has been developed, and proposed in this paper for supporting synthesis in product development on a commercial CAD workspace, while also aiding automated capture and storage of the rationale behind the decisions, for retrieval whenever required during design. This platform is now extended to support analysis of product proposals created so as to automatically extract the information already stored while designing and ask for other information required to model the lifecycle with minimal extra effort from the designer.

Keywords: Sustainable design, Life cycle assessment, Design for environment.

12.1. Introduction

Development of methods to assess the environmental impact of products is increased in recent times and Life cycle assessment (LCA) (Consoli F. *et al.*, 1993)

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has emerged as one of the promising approach for carrying out environmental impact assessment of products and systems. LCA consists of four main stages (a) Goal and Scope Definition, (b) Inventory analysis, (c) Impact Assessment and (d) Improvement assessment. It does not automatically direct us to optimal designs. There are mainly two types of LCAs: (i) full LCA, which requires a lot of time, data and money to carry out, and (ii) abridged LCA, which is may not be reliable as we need to know beforehand what to consider and what to remove from the analysis, leading to uncertainty in calculation. The level of uncertainty involved in the calculation should be available with the results, as decision maker makes decisions based on these results which have uncertainty. Use of LCA and estimation of its uncertainty normally requires environmental experts.

12.2. Objectives and Methodology

The literature review and the empirical studies conducted tried to answer the following questions

- Understand the designers and their needs
- Whether designers generally consider environment as an important criterion in designing?
- How does this consideration change with the availability of information or support for EFPLD?
- What aspects of general designing must be taken into account while developing support for EFPLD?
- What are the needs of designers for EFPLD?
- What are the primary reasons for little utilization of Environmentally Friendly Product Lifecycle Design (EFPLD) tools/methods/guidelines/methodologies in designing?

The Objectives formed to solve these questions are given below

- Develop a holistic framework which will help in both generation and evaluation of environmentally friendly product life cycle design proposals.
- Develop a product design platform which would capture the evolving product information automatically and provide links to browse and reuse the same without extra effort from the designer. Develop a platform
- Develop a method for calculating environmental impact of a product lifecycle proposal and associated uncertainty depending on the information available at that particular point in different dimensions.
- Develop a method for comparing different product lifecycle proposals for various criteria under uncertainty.
- Develop an interactive support for environmentally friendly product lifecycle design proposals.
- Evaluation of the support developed and discusses the actual evaluation results based on design experiments and feed back from the designers.

12.3. Literature Review

Many methodologies have been developed for LCA, like Eco-Indicator 99, EPS 2000, CML2 baseline 2000, EDIP 2003, Impact 2002+, LIME, TRACI, and JEPIX which are region-dependent. LCA provides a means of quantifying impacts and improvements and a means of providing additional directions to the design process. There are different indicators for representing environmental impacts, like MIPS (material intensity per unit service), Ecopoints, Ecoindicators developed for specific regions, etc. There are a number of tools available for material selection but there is no classification according to the environmental aspects of the data (Anne-Marie A., 1999). New eco-design tools are needed for early stages to help identify functional, economic or environmental problems and any associated risks (Jeswiet and Hauschild, 2005).

As impact on the environment comes from all phases of lifecycle, we should not omit some life cycle phases as in streamlined LCA as it may not be clear a priori in which phase of lifecycle the impact will be more for a particular system (Allenby, 1999). The environmental impact of electricity intensive materials (such as virgin aluminium) and production steps will be largely dependent on the geographical location of the supplier (Dewulf, 2003). Environmental issues can trigger innovation and new solutions for old or new purposes have been reported (Ernzer and Bey, 2003).

An iterative use of LCA during product development has been reported to be advantageous (Ritzen and Norell, 2001). The criteria for life cycle oriented designing approaches to be successful are (a) use of environmental effects as one of the criteria for the selection of the final design, (b) focus on functionality of the product, (c) being compatible with existing design procedures, (d) being easy to use, (e) being suitable for teamwork, (f) being useful for both analysis and synthesis, and g) being effective (result versus effort) (Toxopeus and Jong, 1999).

Most of the DfE tools are conceptual in nature and there is very little adoption in the industry. Methods like (Gómez, 2001) are useful for specific phases of the lifecycle of a product. But during product development there is a need to consider the whole lifecycle rather than a single phase of a product. There is no comprehensive method that can be useful for the whole lifecycle of a product in various stages of its design for both synthesis and analysis.

12.4. Empirical Studies

This section concentrates on finding answers to the questions given in section 12.2 by performing the following tasks.

12.4.1. *Analysis of products*

Product analysis is done to see the differences between products for the same functionality. It was carried out on six products to identify the organisation of a product in terms of its sub system, and relationships between these and to understand the information generated. From this analysis we also came to know the relationships between shape, material and manufacturing processes which are used for generic databases.

12.4.2. *Questionnaire 1 & Questionnaire 2*

From literature we understood that designers normally did not consider environment as an important criterion while evaluating the proposals. Literature says some tools/methods are highly used; we want to know why they are highly used and what these constitute which make them highly used and there is very little adoption of environmentally friendly product design (EFPD) tools by designers. We need to investigate these findings.

Questionnaire 1 helps in finding the following information

- In general what criteria designers use for evaluating their proposals and their priority.
- What kind of aids/processes they use in different stages of design for generation and evaluation and their advantages.

Questionaaire 2 gets the following information

- What kind of EFPD aid they need.
- What should be the functionality of the aid in different stages of design for creation and evaluation of proposals?

12.4.3. *Protocol data analysis*

In order to capture a detailed record of the design process, protocol studies have been employed. These are based on the design processes that are captured by audio and video recording. In these studies, the designer was asked to design according to a given design problem. Although the design problem reflects a real world design project, it was limited so that the design process can be completed within a limited amount of time. Three sets of protocol studies, all using 8 individual designers as subjects but with different aids one with normal, second with EFDL literature and third with detailed assessment software are studied in this thesis. In these exercises, the individuals were asked to produce detailed designs for the problems given.

12.4.4. *Discussion*

The needs given in (Lindahl, 2005) and identified in (Kota and Chakrabarti, 2007c) have to be fulfilled. The literature survey, product analysis, questionnaires and design exercises analysis helped in answering the following questions.

What are the limitations of the current LCA (representative) software in Design?

Given below are the questions asked by designers which are not answered by the current software. These questions have to be considered while developing support.

- Can we search the database for materials and processes based on application?
- Can I compare strengths of materials?
- I want to search materials of same strength?
- Can we compare equal functionality material/product?
- Browsing for less impact materials/Processes
- Search for processes required for a particular shape

Is there any difference in impact between products for the same functionality?

There is substantial difference in environmental impact between products with the same functionality

If so what is the reason behind that?

There is a difference in environmental impact as there are changes in the design, in terms of number of parts, number of material types, what processes used for manufacturing, how it is distributed, how it is used, how it is after used.

What needs to be taken in to account while performing life cycle assessment?

We need to have information about the materials used and their inputs and outputs while mining, producing, transferring, manufacturing processes used, assembly processes used, storage processes used, packaging processes used, transportation processes used, installation processes used, consumable required in usage, energy required in usage, maintenance processes used, whether the product reused, remanufactured, recycled, disposed and the data pertaining to these.

What are the primary reasons for little utilisation of Environmentally Friendly Product Design (EFPD) tools/methods/guidelines/methodologies in designing?

They developed in isolation without taking designer's requirements into consideration.

Whether designers generally consider environment as an important criterion in designing?

Designer's consideration of environment as a important criterion is very low.

How does this consideration change with the availability of information or support for EFPD?

Consideration is bettered by the availability of information or support for EFPD.

What aspects of general designing must be taken into account while developing support for EFPD?

Design Stages, outcomes in those stages and activities performed by designers found in those stages have to be taken into account while developing support of EFPLD.

The needs of the designers for developing EFPL are found and are addressed with development of a framework, methods and aid in the following sections.

12.5. ACLODS — A Holistic Framework

A Holistic Framework should consider all the dimensions and their elements identified in Section 12.4. Figure 12.1 **shows** the ACLODS framework.

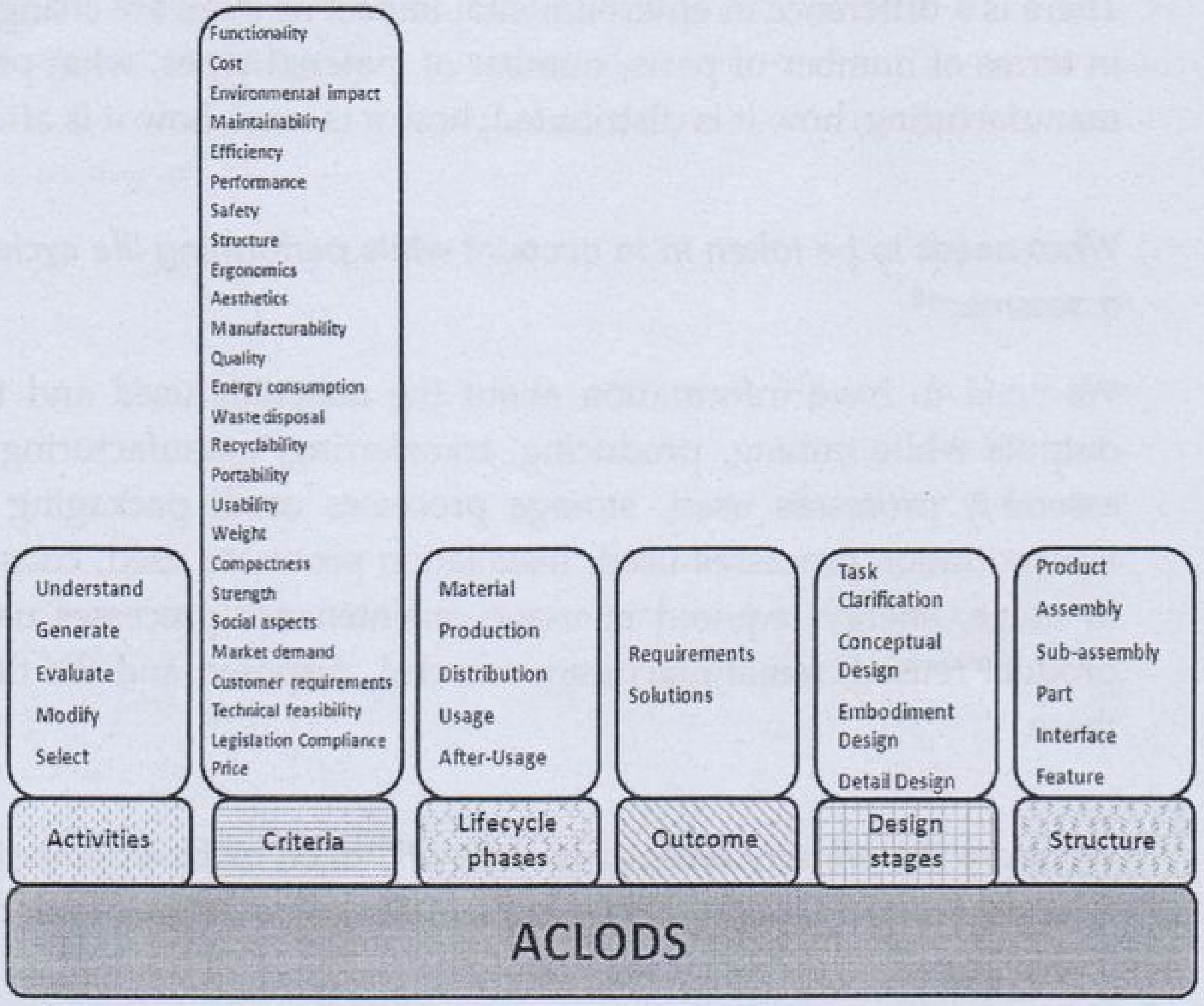


Figure 12.1. ACLODS Framework.

A holistic framework should constitute the following dimensions (a) Activities, (b) Criteria, (c) Lifecycle phases, (d) Outcomes, (e) Design stages, and (f) Structure.

In-house design exercises are conducted to consolidate the elements of the dimensions of the holistic framework for EFPLD; from these, a holistic framework for environmentally friendly product lifecycle design, ACLODS is proposed.

Existing approaches are mapped to the ACLODS framework in order to identify the areas which need improvement; this formed the directions for developing new approaches to fill the gaps and fulfil the overall need. The Design stage and the Product Structure dimensions are the least addressed in the approaches reviewed and should be addressed in combination with the others.

12.6. Rationale Capture Framework

The findings in the previous sections are used to develop a suitable product model schema and a framework for real-time capture and reuse of evolving product information. The framework consists of the following entities: product structure, snaps, events, versions, version tree and audio–video clips. These components are discussed in detail below.

A platform is developed for designers to explore and create product geometry, and be supported in terms of the product evolution through a real-time version tree with snapshots of the structure of the product after each conceivable steps of change to the product. It creates automatically the product structure with parts and relationships for each snapshot. It captures automatically an audio–video record of the product development process carried out by the designer and it divides the captured audio–video record into clips related to the proceedings between every two snapshots of the product structure.

Version tree consists of snaps and events. Each snap is a state of the product structure at that particular instant. Product structure consists of assemblies, subassemblies, parts, relations and features. The typical activities performed by the designers are found and are addressed using the tool.

12.7. Method for Calculating Environmental Impact and Associated Confidence Under Uncertainty

We propose four main categories (Kota and Chakrabarti, 2007a) and sixteen sub-categories of uncertainty in information with respect to LCA in design. The four categories of uncertainty are uncertainty in product structure definition, uncertainty in lifecycle definition, uncertainty in data quality, and uncertainty in methodological choices. The subdivisions of the categories are given below and the uncertainty decreases as the amount of information increases.

1. Uncertainty in structure definition is be subdivided into
    - Uncertainty in assemblies definition (all, some, none)
    - Uncertainty in subassemblies definition (all, some, none)

- Uncertainty in relations definition (all, some, none)
- Uncertainty in parts definition (all, some, none)
- Uncertainty in features definition (all, some, none)

2. Uncertainty in lifecycle definition is subdivided into
   - Uncertainty in material phase (all, some, none)
     Extract, Produce, Distribute
   - Uncertainty in production phase (all, some, none)
     Manufacture, Assembly
   - Uncertainty in distribution phase (all, some, none)
     Package, Transport
   - Uncertainty in usage phase (all, some, none)
     Install, Use, Maintain
   - Uncertainty in after-usage phase (all, some, none)
     Disassembly, Reuse/Remanufacture/Recycle/Disposal, Transportation
3. Uncertainty in data quality is subdivided into
   - Uncertainty in temporal relevance (recent, old, very old)
   - Uncertainty in spatial relevance (local, national, continental, other)
   - Uncertainty in sample size (multiple samples, single sample)
4. Uncertainty in methodological choices is subdivided into
   - Uncertainty in temporal relevance (current, old, too old)
   - Uncertainty in spatial relevance (local, national, continental, other)
   - Uncertainty in comprehensiveness (all, some, none)

At any point of time, uncertainty in information available is a combination of these individual uncertainties. We need to identify what information is required in all dimensions to accurately calculate the environmental impact at a given state of the product, and what information is available in all these dimensions at that particular state of the product; based on these, the uncertainty in an impact estimation is assessed.

There can be uncertainty in the product structure wise meaning the definition of product is uncertain, if the definition is perfect even then there can be uncertainty in terms of the definition of lifecycle, if the definition of lifecycle is perfect even then there can be uncertainty in terms of the data quality, if the data quality is also perfect even then there can be uncertainty in terms of methodological choices for impact assessment.

$$PEI_i\ total = \sum_{l=1}^{\text{no. of lifecycle phases in } i^{th} \text{ product}} PEI_{il}\ LCS \qquad (12.1)$$

$$PC_i\ total = \frac{NZ_L}{NZ_L + Z_L}\left[\frac{\sum_{j=1}^{NZ_L} V_{ij}\ x\ C_{ij}}{\sum_{j=1}^{NZ_L} V_{ij}}\right] + \frac{Z_L}{NZ_L + Z_L}\left[\frac{\sum_{k=1}^{Z_L} C_{ik}}{\sum_{k=1}^{Z_L} C_{ik_{max}}}\right] \quad (12.2)$$

Where

NZ_L – no. of non zero valued lifecycle phases in i^{th} product
Z_L – no. of zero valued lifecycle phases in i^{th} product
V_{ij} – EIV of j^{th} lifecycle phase of i^{th} product
C_{ij} – confidence of j^{th} lifecycle phase of i^{th} product
C_{ik} – confidence of k^{th} lifecycle phase of i^{th} product
$C_{ik_{max}}$ – maximum confidence of k^{th} lifecycle phase of i^{th} product and
For a range of values of V_i we get confidence in range

12.8. Comparative Analysis using Confidence Weighted Objective Method

Values for each criterion are integrated into a single interval value for multiple criteria and the confidence associated with the interval value is estimated as follows.

The integration is done as a confidence weighted sum. The overall value for each alternative is calculated using the following formula:

$$[E_{a_{\min_i}}, E_{a_{\max_i}}] = \sum_{j=1}^{m}\sum_{k=1}^{l} w_{ij}[e_{\min_{ijk}} e_{\max_{ijk}}] \quad (12.3)$$

Its confidence is estimated as follows:

$$[C_{a_{\min_i}} C_{a_{\max_i}}] = \frac{\sum_{j=1}^{m}\sum_{k=1}^{l} (w_{ij})(c_{\min_{ijk}} c_{\max_{ijk}})(e_{\min_{ijk}} e_{\max_{ijk}})}{\sum_{j=1}^{m}\sum_{k=1}^{l} (w_{ij})(e_{\min_{ijk}} e_{\max_{ijk}})} \quad (12.4)$$

i – identifier for the alternative
j – identifier for the criterion
k – identifier for the lifecycle phase
m – total number of criteria
l – total number of lifecycle phases
w_{ij} – weighting factor of i^{th} alternative j^{th} criterion
$c_{\max_{ijk}}$ – maximum confidence of i^{th} alternative j^{th} criterion K^{th} lifecycle phase

$c_{\min_{ijk}}$ – minimum confidence of i^{th} alternative j^{th} criterion k^{th} lifecycle phase

$e_{\max_{ijk}}$ – maximum ineffectiveness of i^{th} alternative j^{th} criterion k^{th} lifecycle phase

$e_{\min_{ijk}}$ – minimum ineffectiveness of i^{th} alternative j^{th} criterion k^{th} lifecycle phase

This is because the overall confidence for the integrated value is a weighted sum of individual confidence where the weights are proportional to the component of the value affected by the corresponding confidence. The details can be found in (Kota and Chakrabarti, 2007b)

12.9. IDEA-SUSTAIN — A Prototype Development

The developed platform in Section 12.6 is now extended to support environmental impact analysis of product proposals created by automatically extracting information already stored while designing and asking for other information required to model the lifecycle, with minimal extra effort from the designer. It then uses a method for uncertainty reasoning developed in Section 12.7 to estimate the level of confidence on the impact value owing to the incompleteness in information available. The estimation is possible at component, assembly or product levels, for a single lifecycle stage or multiple stages. For impact estimation, we used Ecoindicator99 methodology as the basis. The overview of the implemented prototype is shown in Figure 12.2. It consists of 6 modules which are given in the figure below.

Details regarding version tree, snaps, events etc can be found in (Chakrabarti, Kota, Rao and Chowdary, 2005).

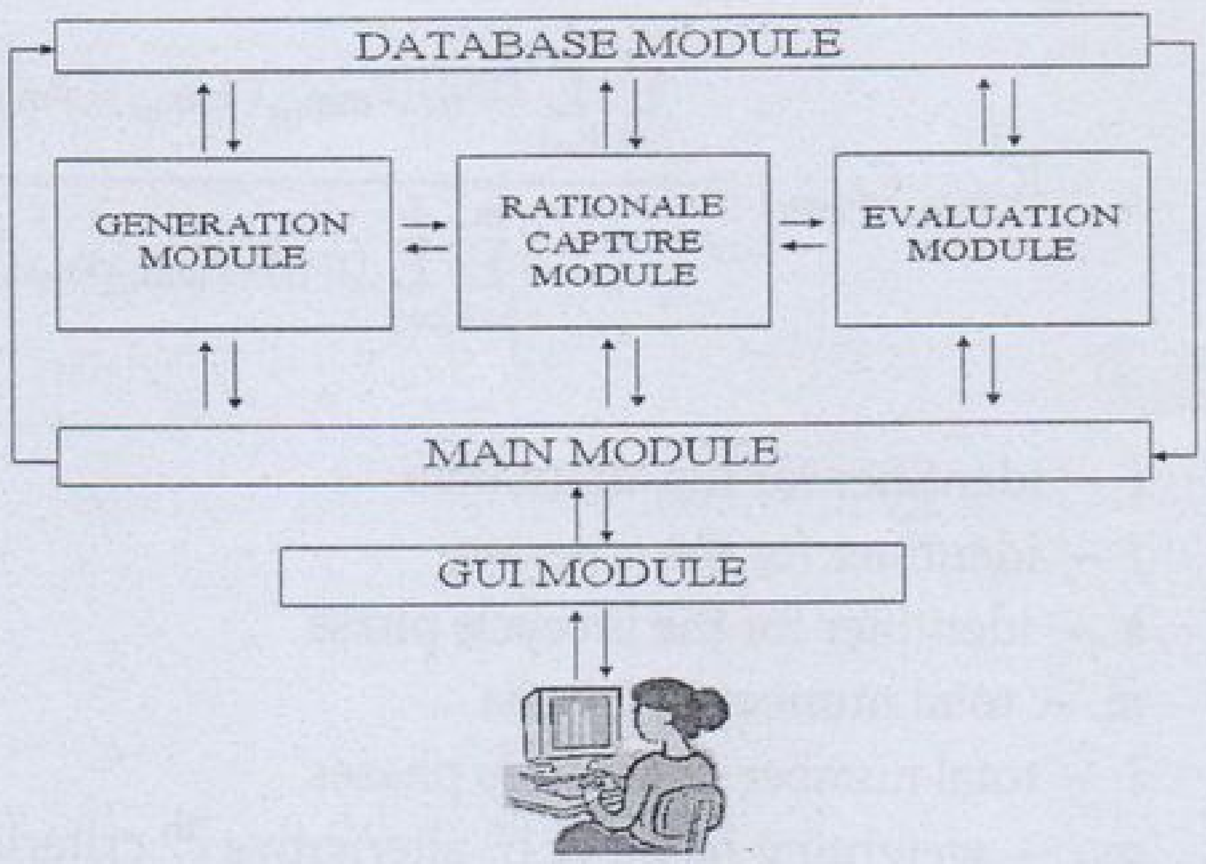
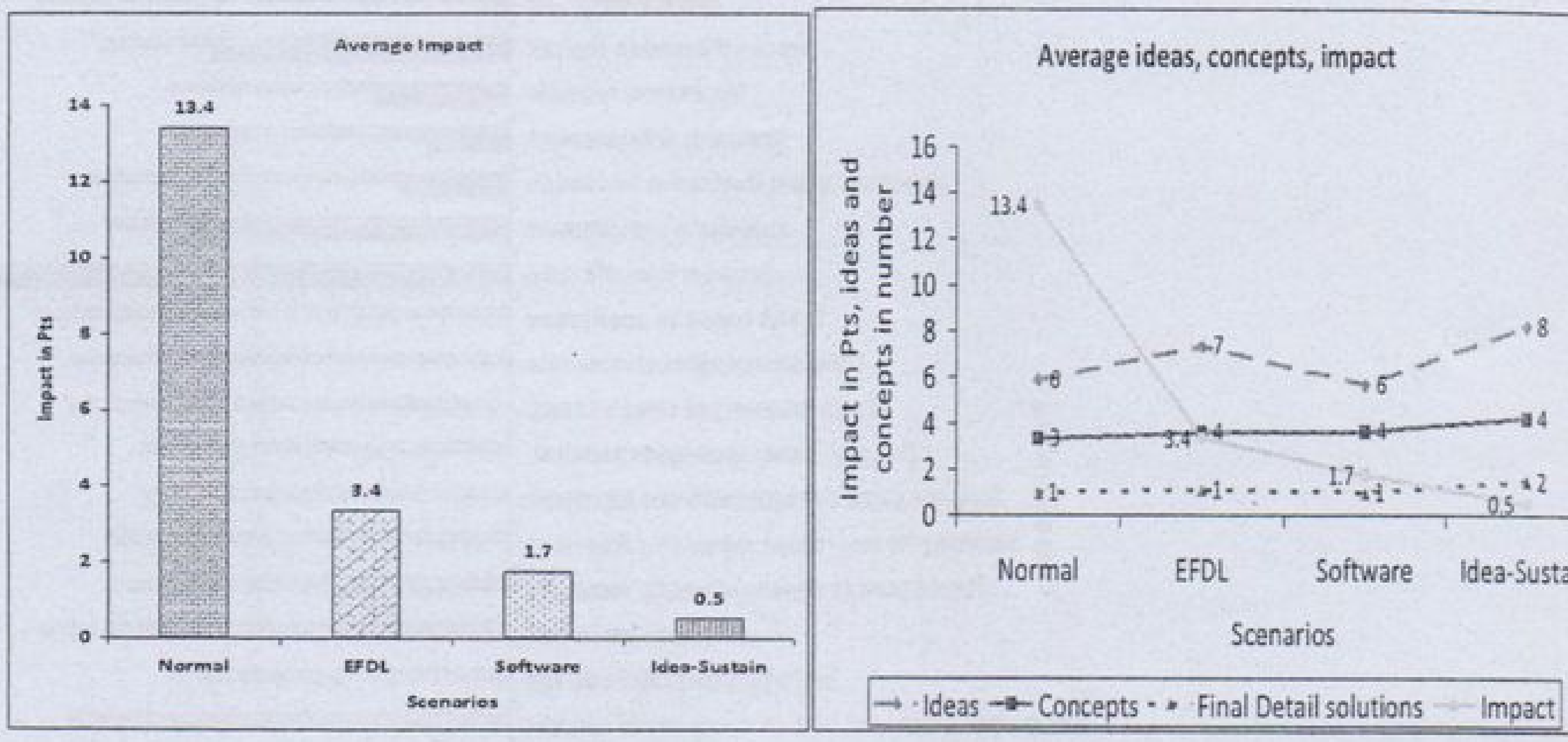


Figure 12.2. Overview of IDEA-SUSTAIN.

12.10. Evaluation of IDEA-SUSTAIN

12.10.1. *Compare the results with the earlier experiments for defined criteria*

The following Figure 12.3 shows the average impact across all the problem using different aids. First bar shows the average impact of all the problems solved by Normal way, second bar shows the average impact of all the problems solved by EFDL, third bar shows the average impact of all the problems solved by Software (LCA), and the fourth bar shows the average impact of all the problems solved by Idea-Sustain. In this also the average lifecycle impact across four problems is least (0.51Pts) with Idea-Sustain.



Figures 12.3 & 12.4. Average impacts, ideas, concepts across four problems using different aids.

The above Figure 12.4 shows the comparison of average number of ideas produced, average number of concepts developed, average number of detailed solutions from those and the average impact across all problems in different scenarios. We can see that the number is more in Idea-Sustain and impact is less. Thus the developed aid helped in reducing the environmental impact and increase in generation of more ideas and concepts. The number of ideas generated and number of concepts developed by a particular. From the above comparisons we can see that the developed software has helped in reducing the lifecycle impact very well. The next section evaluates the usefulness of the aid in terms of the derived requirements for EFPLD.

12.10.2. *Usefulness/Requirement fulfillment*

12.10.2.1. *Feedback form*

The designers were asked to give the feedback against the following requirements identified for the tool. They need to select on the scale of 1–5, 1 being not

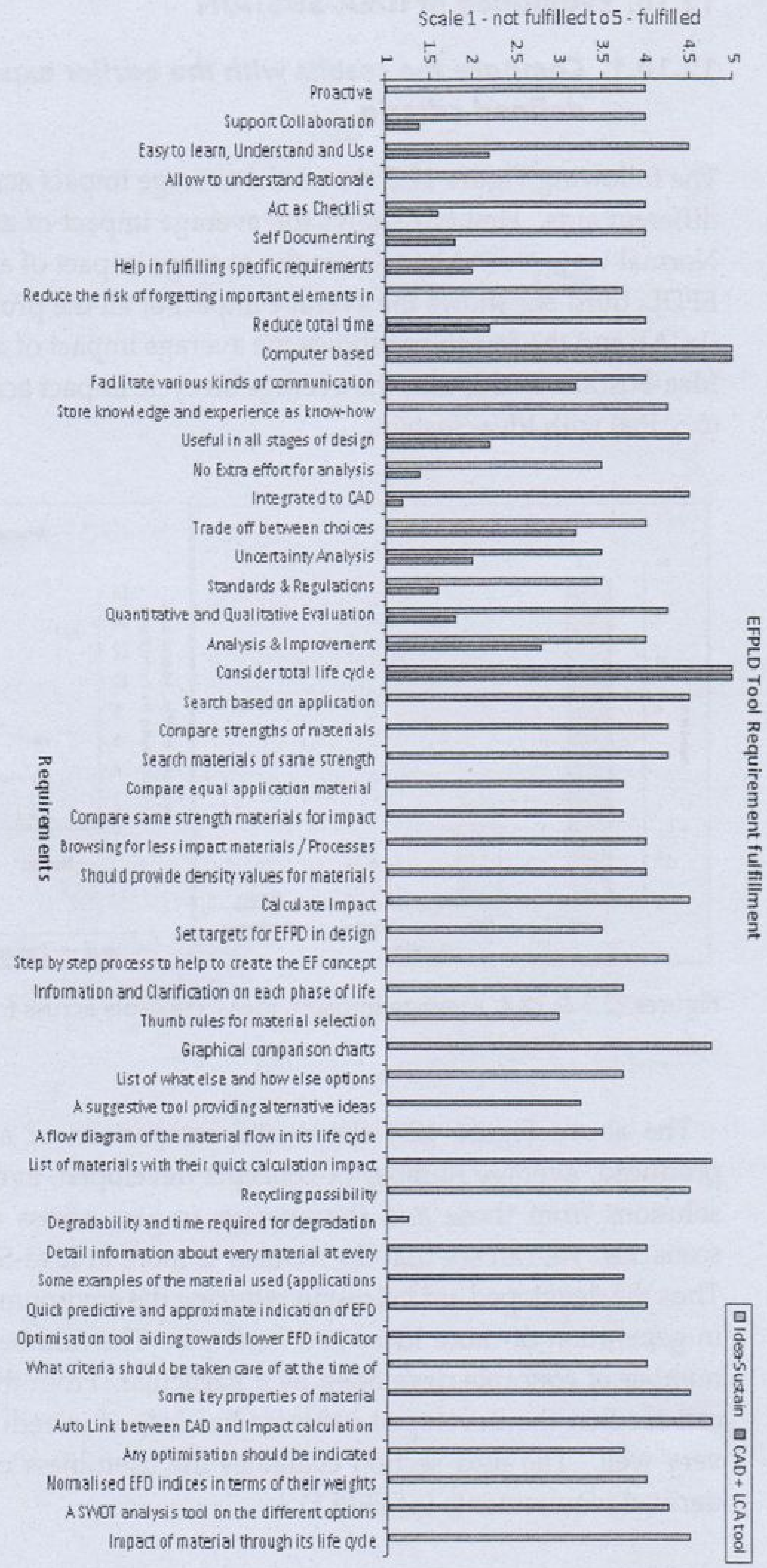


Figure 12.5. Comparison of Idea-Sustain and Software (LCA) for fulfilment of EFPLD requirements.

fulfilled and 5 being completely fulfilled. The items in blue colour are the derived requirements from literature and empirical studies and the items in black colour are derived from the wishes of the designers participated in empirical studies. The feedback given by the designers for each requirement is averaged and plotted in the coming Figure 12.5. Two aids Software (LCA) and Idea-Sustain are compared for fulfilment of the requirements by the feedback given by the designers after participating in the respective design exercises.

12.10.2.2. *Analysis of feedback forms*

We can see from the Figure 12.5 most of the requirements are highly fulfilled by the Idea-Sustain where as the fulfilment index for the Software (LCA) is very less according to the designers participated in the exercises. The Software (LCA) did not fulfil requirements like understanding rationale, forgetting important elements in PD, storing of expert knowledge as know-how backup etc., where as Idea-Sustain fulfilled those and the other needs of designers which are lacking in Software (LCA). Thus Idea-Sustain is useful in generation as well as evaluation of the environmentally friendly product lifecycle proposals.

12.11. Conclusions

A holistic framework proposed which constitute the following dimensions (a) Activities, (b) Criteria, (c) Lifecycle phases, (d) Outcomes, (e) Design stages, and (f) Structure.

A method called confidence weighted objective method (CWOM) is developed for use in multi-criteria decision making for lifecycle designs of product systems under uncertainty. An understanding is developed on uncertainty related to different dimensions as product structure, lifecycle phases, information using empirical studies and this understanding is used in developing the method and guidelines for evaluation of product lifecycle alternatives under uncertainty.

The developed aid Idea-Sustain is evaluated by using four designers solving four problems using Idea-Sustain to see whether all the functional requirements are achieved by the aid while solving the problems. The usage of Idea-Sustain is encouraging for generation as well as evaluation. Idea-Sustain fulfilled most of the needs in highly effective manner where as the software (LCA) partially fulfilled some of the needs. There are other wishes of the designers after using software (LCA) which are not available there and fulfilled by the developed aid Idea-Sustain.

of EFPLD

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